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A review on silt erosion in hydro turbines

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Abstract

Erosive wear of hydro turbine runners is a complex phenomenon, which depends upon different parameters such as silt size, hardness and concentration, velocity of water, and base material properties. The efficiency of the turbine decreases with the increase in the erosive wear and final breakdown of hydro turbines. Various researchers have conducted experiments to study the effect of these parameters on erosive wear, but most of these experiments are on small-size samples in different types of test rigs to simulate the flow conditions in the turbine, but actual flow conditions and the phenomenon of erosive wear are too complex to simulate. In the present paper, studies undertaken in this field by several investigators have been discussed extensively. Based on literature survey various aspects related to silt erosion in hydro turbines, different causes for the declined performance and efficiency of the hydro turbines and suitable remedial measures suggested by various investigators have been discussed.

Keywords: Hydro turbine; Silt erosion; Erosive wear; Performance; Efficiency

Contents

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Nomenclature

a	average grain size coefficient of suspended sediment with a base of 0.05 mm
C	solid concentration
c	mean sand concentration
C_w	fraction of solid by weight
d	particle size
d_{50}	median particle size (m)
$f(d_{p50})$	function defining particle size
k	normal component of particle impact velocity needed to initiate the erosion
k_1, k_2, k_3	coefficient to account for shape, hardness and abrasion resistance of base metal, respectively
M	the total mass of impacting particles
M_r	coefficient of wear resistance of base material
PE	modified suspended sediment content
P	the average annual suspended sediment content in g/l
p	a constant
q	quartz content (hard particle content)
S_1	coefficient of silt concentration
S_2	coefficient of silt hardness
S_3	coefficient of silt particle size
S_4	coefficient of silt particle shape
TA	turbine abrasion
V	velocity of particle
v	relative jet velocity
v_f	flow velocity (m/s)
W	wear rate (kg/h)
W_d	deformation wear at normal impact condition
z	exponent for relative velocity
α	exponent for annual suspended sediments content
β	exponent for average grain size coefficient
θ	impact angle
δ	abrasion rate (μm/h)
ε	deformation factor
K, β, γ and φ	constants whose values depend on the properties of the erodent as well as the target material
η_m	turbine peak efficiency with sediment laden flow
η_w	turbine peak efficiency with clean water

1. Introduction

Energy is one of the key factors that influence the development of a nation providing economic and social benefits to its people. This is more important in developing countries like India, for economic development at micro level necessitating the need for the

availability of secure and sustainable energy. The different sources of energy are hydro, thermal, nuclear and non-conventional energy resources like wind, solar and biomass. Presently in India the total installed capacity including all the resources is 126,089 MW, of which the share of the hydro energy is 26% [1], whereas an ideal hydrothermal mix should be 40:60. Among the different sources of energy, hydropower is recognized as a renewable source of energy, which is economical, non-polluting and environment friendly. India is blessed with immense amount of hydroelectric potential and only 17% of the hydro potential has been harnessed till now [1]. Hence, a lot of importance is being given to develop the hydropower potential. Ministry of Power has been entrusted to develop large hydropower resources and Ministry of Non-conventional Energy Resources has been promoting small and mini hydro projects ($\leqslant$25 MW) so as to provide energy to remote and hilly areas. The management of the small hydropower plants for achieving higher efficiency of hydro turbines with time is an important factor, but the turbines show declined performance after few years of operation as they get severely damaged due to various reasons. One of the important reasons is erosive wear of the turbines due to high content of abrasive material during monsoon. This problem is a major concern in the case of small hydropower plants, as most of these plants are run-of-river schemes and are situated in steep hilly terrains. During the rainy season, a large amount of sediment (as high as 20,000 ppm) is present in water and it becomes difficult to remove all these sediments before passing through the turbine. The silt mainly consists of quartz (70–98%), which is extremely hard (hardness 7 in Moh's scale) causing severe damage to the turbine components [2–4] like water passage components, guide vane, top and bottom ring liners, labyrinths, runner blades, inlet valve seals, etc. Erosion wear effect in hydro turbines results in alteration of blade profile, increased vibration, fatigue damage, inefficient operation and system failure.

Erosive wear of the turbine blades is a complex phenomenon that depends on (i) eroding particles, their size, shape, hardness and concentration (ii) substrates, chemistry, elastic properties, surface hardness and surface morphology and (iii) operating conditions, velocity and impingement angle [5,6]. It should be emphasized that sand erosion even with grain size less than 60 μm has led to severe damage of needles and nozzles of a Pelton turbine, which is caused by the strong turbulence in the high jet velocity bringing the particles to oscillate and rotate in circles causing collisions with the steel surface. If coarse sand is present, the Pelton buckets are also severely eroded while the damage of the nozzles may be less serious. The reason may be explained by the extreme acceleration of a particle passing the Pelton bucket. A flow analysis shows that an acceleration of 100,000 m/s^2 may occur for small buckets in a high head turbine [5].

The erodent shape is an important property, but its effect is difficult to quantify for natural particles. For impact of spherical particles on ductile materials, Hutchings and Winter [7] assumed ploughing of material forming lips around the crater, which breaks up in subsequent impacts. In another study, Winter and Hutchings [8] have shown that the angular particles remove the material by ploughing and micro cutting for lead and mild steel. Desale et al. [9] have shown that the surface morphology of substrate material has deep craters and higher value of average surface roughness for angular erodent particles compared with the blocky shape erodents. The present paper discusses the studies carried out by various investigators in order to determine the effect of erosive wear and identify the gaps for future studies.

2. Theoretical investigations

Generally, erosion damage is considered as the gradual removal of material caused by repeated deformation and cutting actions. Sand erosion is designated as abrasive wear. This type of wear will break down the oxide layer on the flow guiding surfaces and partly make the surfaces uneven which may also be the origin for cavitation erosion. Sand erosion therefore may be both a releasing and contributing cause for damages that are observed in power plants with a large transport of wearing contaminants in the water flow. The actual mechanism of erosive wear was not fully understood. Therefore, a simple, reliable and generalized quantitative model for erosion could not be developed. Most common expression for the erosive wear was based on experimental experiences. The hydro-abrasive wear was commonly quantified by means of wear rate W, defined by loss of mass per unit time and generally expressed as

$$W = f(\text{properties of eroding particles, properties of base material and operating conditions}).$$

Kjolle [5] studied the causes of damages in hydro turbines and found that the main causes of damage of water turbines were due to cavitation problems, sand erosion, material defects and fatigue. The turbine parts exposed to cavitation are the runners and draft tube cones for the Francis, Kaplan and the needles, nozzles and the runner buckets of the Pelton turbines. The effect of cavitation erosion was found to be reduced by improving the hydraulic design and production of components, adopting erosion resistant materials and arrangement of the turbines for operations within the good range of acceptable cavitation conditions.

Neilson and Gilchrist [10] studied the total wear at normal impact angle assuming the total wear to be contributed by only deformation wear, which gives a deformation factor (ε) as below:

$$\varepsilon = \frac{W_\mathrm{d}}{\frac{1}{2}M(V\,\sin\theta - k)^2}, \tag{1}$$

where W_d is deformation wear at normal impact condition, 'M' is the total mass of impacting particles, 'V' is velocity of particle, θ is impact angle and k is the normal component of particle impact velocity needed to initiate the erosion which is generally neglected, considering very small compared to the impact velocity.

Bain et al. [12,13] have attempted to develop a correlation for the estimation of erosion rate based on extensive data collected in a bench scale test rig. The general form of the correlation can be represented as,

$$W = KV^{\beta}d^{\gamma}C^{\varphi}, \tag{2}$$

where W is erosion rate, V is velocity of particle, d is particle size, C is solid concentration, and K, β, γ and φ are constants whose values depend on the properties of the erodent as well as the target material. For different erodents, the effect of particle size has been normally considered as a parameter affecting the wear and the exponent value 'γ' was found to lie between 0.3 and 1.6 [11–17].

The hydraulic performance tests on a Francis turbine model with sediment laden flow, conducted in Japan and reported by Okamura and Sato [18], showed that the turbine's best efficiency decreased in direct proportion to the increase in solids concentration. The

efficiency was correlated by the following expression:

$$\eta_{\mathrm{m}} = (1 - 0.085C_{\mathrm{w}})\eta_{\mathrm{w}}, \tag{3}$$

where η_{m} is turbine peak efficiency with sediment-laden flow, η_{w} is turbine peak efficiency with clean water, and C_{w} is fraction of solid by weight.

Sundararajan [19] presented a comprehensive theoretical model for erosion, valid for all impact angles combining the concept of localization of plastic deformation leading to lip formation and the generalized energy absorption relations valid for all impact angles and all shapes of eroding particles.

Krause and Grein [20] reported that the abrasion rate on conventional steel Pelton runner made of X5CrNi 13/4 was as given below,

$$\delta = pqcv^{3.4}f\,(\mathrm{d}_{\mathrm{p}50}), \tag{4}$$

where δ is abrasion rate (μm/h), p is a constant, q is quartz content, c is mean sand concentration, and v is relative jet velocity; $f(\mathrm{d}_{\mathrm{p}50})$ is function defining particle size.

Since the above equation had been proposed for X5 CrNi 13/4, it is applicable to turbine components made of this material only.

Naidu [21] suggested the following expression for predicting the silt erosion rate:

$$W = S_1S_2S_3S_4M_{\mathrm{r}}v^x, \tag{5}$$

where S_1 is coefficient of silt concentration, S_2 is coefficient of silt hardness, S_3 is coefficient of silt particle size, S_4 is coefficient of silt particle shape, M_{r} is coefficient of wear resistance of base material, and v is relative velocity of water.

The values suggested for the exponent X are: 3 for Francis runner, 2.5 for guide vanes and pivot ring liner, 2.5 for Pelton nozzle and 1.5 for Pelton runner buckets.

Wear occurs by the plastic displacement of surface and near surface material and by the detachment of particles that form wear debris. This is caused by the frictional contact of flowing water or by solid silt particles entrained in flowing water. Severe impact of silt particles on the blade surfaces contributes significantly to the erosion and wear. When the silt is composed of hard abrasive particles, wear is caused by cutting action of these particles [22].

The turbine abrasion was expressed by Asthana [23] as

$$\mathrm{TA} = f\,(\mathrm{PE}, v^z), \tag{6}$$

where PE is modified suspended sediment content, v is relative velocity between flowing water and turbine parts where abrasion is severe, and z is exponent for relative velocity.

The modified sediment content (PE) is expressed by the following equation:

$$\mathrm{PE} = P^{\alpha}a^{\beta}k_1k_2k_3, \tag{7}$$

where P is the average annual suspended sediment content in gm/l. It is based on the long-term measurements in the river; α is exponent of 'P' representing correction factor for suspended sediment concentration. It is taken as 1 for concentration up to 5 g/l; a is average grain size coefficient of suspended sediment with a base of 0.05 mm; β is exponent of 'a' representing correction factor for average particle size, which was taken as 1 for particle up to 0.6 mm and curved flow; k_1, k_2, k_3, represent the coefficient to account for shape, hardness and abrasion resistance of base metal, respectively. k_1 is taken as 0.75, 1.0 and 1.25 depending on irregularities ranging from few to severe, k_2 was taken as 1 for

hardness greater than 3 (on Moh's scale) and 0.5 for less than 3, k_3 was taken as 1 for 13Cr4Ni steel.

Schneider and Kächele [24] proposed that wear rate, W was a function of a multitude of parameters as shown in the following algebraic relation:

$$W \sim cqf\,(d_{50})\,v_{\mathrm{f}}^{n}, \tag{8}$$

where c (kg/m^3) is sand concentration, q (kg/kg) is hard particle contents, d_{50} (m) is median particle size, and v_{f} (m/s) is flow velocity.

The authors suggested that the value of n varied considerably from about 2.1 to more than 3. This range of values was reported to reflect the limitations of the algebraic relation, which considered neither the material parameters of the eroded body nor the flow parameters or the various material parameters of the silt particles.

Mack et al. [25] suggested a numerical model to predict the erosion on guide vanes and on labyrinth seals in hydraulic turbines. The prediction of erosion, based on the Lagrangian calculation of particle paths in a viscous flow, was described for two components of a Francis turbine, for which results of field tests were available. It was shown that the erosion level was strongly dependent on the particle size. A fully 3D flow and erosion calculation around the guide vanes of the same Francis turbine was presented. It was shown that the geometry of the guide vane including tip clearance, support and fillets lead to a complex flow field, which, as a consequence, resulted in a complicated fluid–particle interaction strongly affecting the erosion pattern. There was a good agreement between the numerically obtained erosion pattern and the field test measurements.

Keck et al. [26] presented a study on the utilization of CFD method to predict the erosion pattern in a hydraulic turbine and compared it with field measurements of the erosion. Sand erosion was modeled by applying the Lagrange method i.e. tracking a large number of individual particles in the flow field. The motion of the particles was described by the Basset–Boussinesq–Oseen equation whereby experimentally based correlations were used for the drag and the influence of turbulent motion. During the Lagrangian tracking, the number of particles impinging on a surface was recorded. Out of these data the removal of the wall was calculated. Calculations were performed for different particle sizes. The result showed a good correlation for the erosion pattern with the field observation. However, the authors concluded that CFD simulation did not provide accurate absolute erosion, although it could be used to obtain relative erosion intensities and to evaluate different designs relative to each other.

3. Experimental studies

Many investigators reported their experimental results on erosive wear conducted with different base materials and different types of erodent.

Chattopadhyay [27] conducted experiments to determine the slurry erosion characteristics of AISI 316L, 15 wt% Cr—15 wt% Mn stainless steel and Stellite powder alloy applied as a overlay to cast ferritic stainless steel of CA6NM type, which was used as a normal turbine runner material. The tests were conducted in specially designed test equipment (Fig. 1). The different wear rates of the alloys were explained in terms of the microstructure, hardness and work hardening rate. The samples were rectangular in section and of size 65 mm × 14 mm × 20 mm and thick sand slurry was the erodent. The

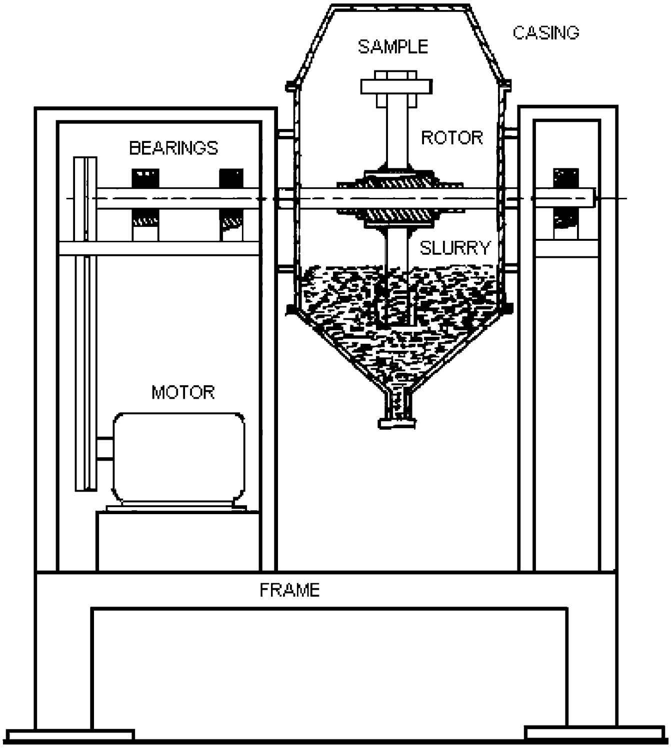

Fig. 1. Schematic diagram of slurry erosion test equipment [27].

author had concluded that 15 wt% Cr—15 wt% Mn stainless steel and Stellite powder alloy applied as a overlay showed better erosion resistance properties as compared with the base material CA6NM steel.

Krause and Grein [20] carried model tests with varying parameters with the X5 CrNi 13/4 steel, normally used in hydro plants. The test rig was designed to simulate the flow conditions in a turbine. A natural sand/water mixture taken from a power plant reservoir and sand containing 99% quartz in various grain sizes were used for the tests. They have concluded that the abrasion rate is a function of velocity, sand content and proportion of hard components and size of the sand particles. The maximum abrasion occurred within an approximate particle size range of 40–70 μm.

Roman et al. [28] reported the development of a new erosion resistant coating NEYRCO—a composite coating with ceramic and organic matter base, designed to combine hardness and ductility. They carried out a series of model tests in a specially designed test rig (Fig. 2) to find the effectiveness of the coating against erosion. Four water velocities were used: 20, 25, 36, and 48 m/s. The water flow rate was 2.5 l/s. The abrasive material was high silica content with the following chemical composition:

SiO_2	$>99.5\%$
$Al_{12}O$	$>0.2\%$
Fe_2O_3	$>0.2\%$

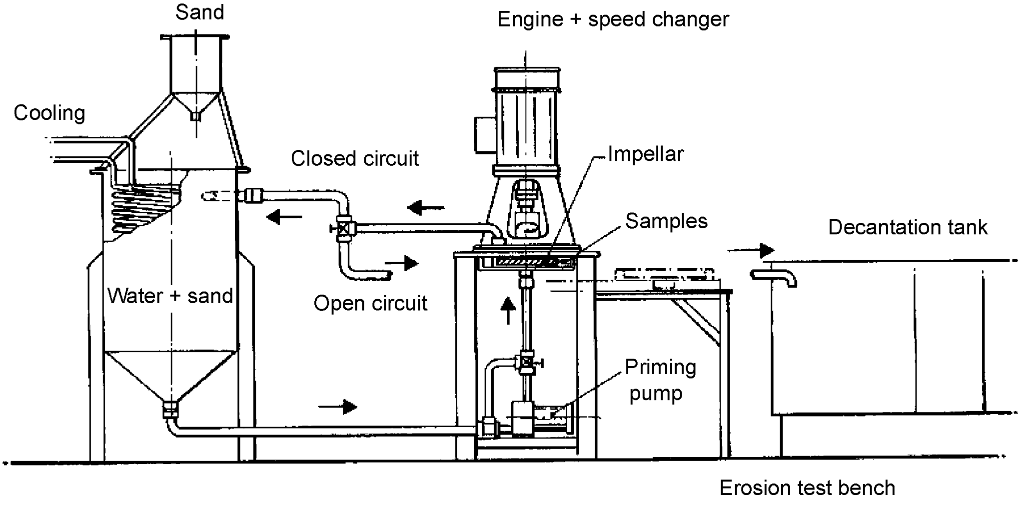

Fig. 2. Schematic diagram of laboratory test equipment [28].

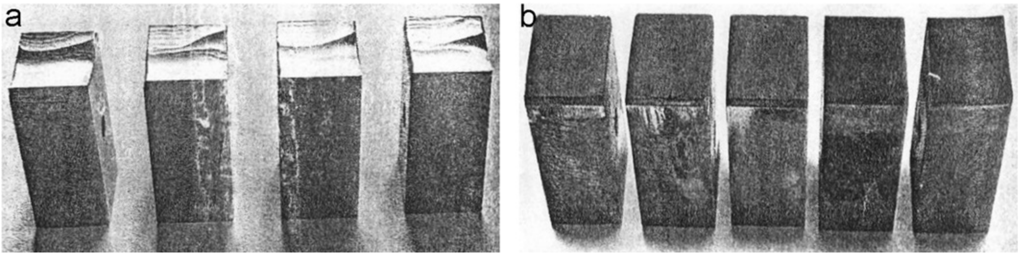

Fig. 3. (a) Wear waves on stainless steel and (b) wear waves on Neyrco [28].

$CaCO_3$	$>0.04\%$
Size	200–400 μm
Hardness	7 Mohs
Concentration	20 g/l

Surface examinations of the samples subjected to same erosive condition showed that the coated samples gave better performance as compared with the uncoated samples (Fig. 3a and b).

Mann [6] studied the erosion resistance characteristics of different hard coatings such as hard chrome plating, plasma nitriding, D-gun spraying, and boronising with commonly used steel in hydro turbines. The wear test facility was designed considering the low and high impact wear of hydro turbine components. The samples used were cylindrical in shape to simulate the angle of impingement from 0° to 90°, which occurred in hydro turbine blades and vanes. Sand was used as the erodent, the concentration varied from 1500 to 10,000 ppm. Performance of borided T410 steel was found much better than others.

Mann and Arya [29] studied the silt erosion characteristics of plasma nitriding and HVOF coatings along with commonly used steel in hydro turbines. The characterization of

abrasive wear was carried out as per ASTM G-65. Angle of incidence, velocity and Reynolds numbers were maintained similar to those that commonly occur in hydro turbines, simulating low as well as high-energy impingement wear. The test parameters adopted are given below:

1 kg mineral sand of hardness	1100 HV
Size of erodent	180–250 μm
Erodent flow rate	5.5 g/s
Sample size	75 mm × 25 mm × 6 mm

HVOF coating showed superior performance than plasma nitrided steel, but the demerits of HVOF coating was that it showed micro cracking, debonding and digging out of WC particles. For plasma nitrided steels there was ductile mode of erosion.

Engelhardt and Oechsle [30] examined different materials and coatings to evaluate their resistance to the hydraulic turbine surface. A hard, HVOF-applied TC/CoCr coating, named Diaturb 532 and a soft PU-based coating called Softurb 80 were chosen for testing. The samples were tested in a test rig. Later, the San Men Xia hydro power plant in China's Henan province was chosen for full scale testing of the improvements found during the laboratory research programme. The project included a monitoring phase of 2 years, during which the turbine parts were inspected several times. Except for some mechanical damage to the protection systems, wear rates on the HVOF-coated runner blades were determined to be within the accuracy of the thickness measurement gauge (<40 μm). The wear rate on the PU-coated surface of the runner blades and the guide vanes was determined to be around 0.15 mm per year. The unit was in operation during the 2-year monitoring phase and also during the flooding season with an average sand concentration of 20–30 kg/m^3.

Thapa and Brekke [31] carried out laboratory erosion experiments on curved specimens by particles of different size to simulate the flow in Pelton bucket in a high-velocity test rig (Fig. 4). Aluminum specimens with different curvature (Fig. 5) were used for the testing. Baskarp-15 foundry sand with 66% free quartz (fine sand) of size 174 μm and artificial silica sand (coarse sand) of size 256 μm were used as the erosive particles. The results were

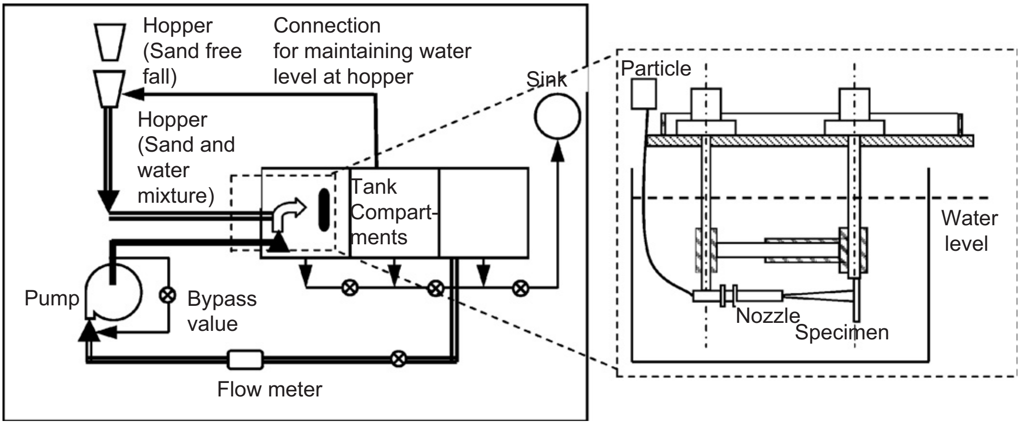

Fig. 4. High velocity test rig. [31].

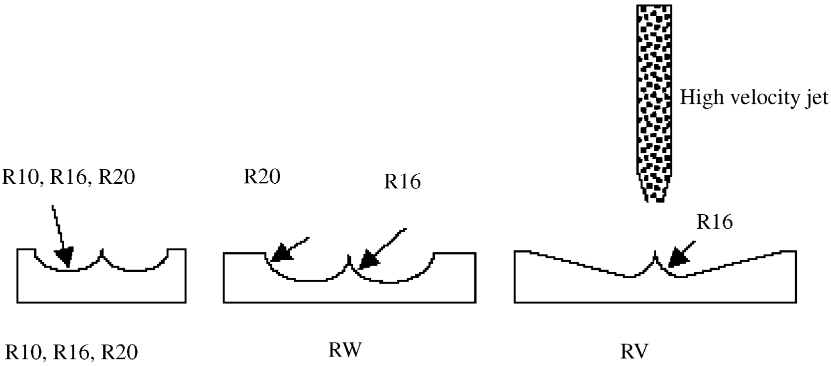

Fig. 5. Specimens of different curvature [31].

presented in the form of erosion rate for different profiles and surface roughness at different locations of curved specimens. By visual observation of eroded particles the authors concluded that most of the coarse grains strike close to the splitter, whereas the fine grains were observed far away from the splitter. The erosion rate in terms of weight loss per unit striking particle found smaller with fine particles. This was due to low particle impact energy of smaller particles and might be because some of the fine particles escaped gliding without striking the surface. Another observation they made was erosion rate in mg/kg increased with the increase in curve radius.

4. Case studies

Ahluwalia et al. [32] suggested a number of measures such as providing adequate desilting arrangements, facilities for quick segregation and easy access to vulnerable parts, judicious choice of the type of turbine as well as operating speeds, use of stainless steel materials and availability of skilled maintenance staff to evaluate techno-economic considerations for hydropower stations in India. They also emphasized that the above recommendation can only reduce the erosion problem by extending the period between the shot downs but cannot eliminate the same in the underwater turbine parts totally.

Singh [33] reported the case study of the Tiloth hydropower station (3×30 MW) on river Bhagirathi. The three units were commissioned in 1984. The turbines were found to be seriously damaged after about 2600 h of operation. They were repaired, but extensive damage was observed again within 3000–5000 h of operation. The sedimentation chamber had been designed to arrest silt particles larger than 0.3 mm. Petrographic studies carried out revealed the presence of highly abrasive quartz, having hardness of 7 on Moh's scale. The concentration of the silt particles during the rainy season was maximum and reached up to 4000 ppm. Initially, there was a proposal to provide another sedimentation chamber to arrest particles up to 0.15 mm. But due to very high cost and as the settling chambers could not completely remove the silt particles, the proposal was not implemented. The investigators, rather, suggested improving the metallurgy of the turbine blades. The new runner was manufactured with stainless steel (13 Cr 4 Ni), which was supposed to give a better performance regarding erosion. However, it was observed that there was no appreciable reduction in the erosion compared with the older runners.

Yan [34] studied the effect of silt abrasion in different hydropower plants of China and had drawn the following conclusions:

i. The abrasion remained moderate for all particles smaller than 0.05 mm and rises sharply for larger sizes.
ii. The product of operating head H and content of harmful sediment S_d ($d > 0.05$ mm) must be less than 7, so that the abrasive erosion in the turbine would be minimum.

Kumar et al. [35] reported the case study of Tiloth Power station under Maneri Bhali Stage-I Project, which is basically a run-of-river scheme, at river Bhagirathi between Maneri and Uttarkashi (India). Detailed examination of runner blades of Unit-I revealed that there was thinning at outlet edges due to heavy erosion along with pitting marks before 1 year of commissioning. The analysis indicated that thinning of blade was caused by silt erosion. There was also heavy leakage of water from the guide vane bush housings. Subsequent inspection of under water parts revealed that the runner blades have been extensively damaged and big pieces of 300 mm × 350 mm size has just sheared off. Further, visual examination revealed that there were more cracks near the skirt of the runner blades. In Unit-II and Unit-III, the extend of damage to the runner blades was similar to the damage noticed in Unit-I. Such an extensive damage is expected to be caused due to excessive silt, designed/operating condition, metallurgy of blades and inadequate design of runner profile.

According to Singh et al. [36], right from the inception of the project, design and layout need to be planned in such a way that there is minimum damage at acceptable economic cost. Speed selection of unit, features ensuring easy and fast replacement of effected parts, etc. can help reduce drastically the downtime period. The problem of silt erosion is more peculiar to Indian conditions and therefore efforts are required to generate adequate data to deal with the problem. In view of no guarantees offered by the supplier, purchaser is hesitant to experiment with protective coating on underwater parts because of its high cost.

Mathur et al. [37] reported the case study of Salal (6 × 115 MW) hydropower station on river Chenab and Baira Siul (3 × 60 MW) hydropower station on river Baira and Siul. The silt contents of the water of above rivers indicated the presence of 75–98% quartz bearing hardness 7–8 on Moh's scale and about 98% silt particles are of size 0.25 mm and less. After 4000 h of operation at Baira Siul guide vanes made of 13Cr4Ni stainless steel, the loss was about 10–15% whereas at Salal this loss was approximately 10–12% of design weight. Stay vanes made of carbon steel get eroded. Pressure side of runner blades, crown and skirt get eroded very fast. In 2 years of operation runner profile gets altered. Labyrinth gap in Baira Siul increased from the design value of 0.8–1.2 to 3–4 mm in only 1 year of operation. At Salal, lower labyrinth ring and sometimes portions of lower ring skirt get washed away in 8–10 thousand hours of operation of machines. Such type of erosion caused increase in the vibration level of machines at both power stations.

Wood [38] reported a field study carried out by China North West Electric Power by mounting coated specimens in different places in Kaplan and Francis turbines and left during the flood season. Coated region had reduced the worn out thickness between 5 and 43 μm, whereas the surrounding uncoated metal had been worn down by between 1 and 10 mm. The research programme concluded that minimum loss of efficiency can only be reached by a combination of design optimization, based on erosion prediction and protection of surfaces with wears reducing coatings.

Pradhan [39] observed during his studies that in run-of-river power plants in steep sediment loaded rivers the conventional design criteria to trap 0.2 mm size sediment particles did not seem to function satisfactorily. In general, projects were having damages to runners due to severe erosion caused by silt. In case of Jhimruk Project, the wear on runner was so high that it required repair after every monsoon. A case study was carried out for JHP, a 12-MW run-of-river type project built and commissioned in 1994. The settling basins had been designed to trap 90% of 0.2 mm size particles. During the sediment monitoring programme, the investigators observed that average values for suspended sediment concentration in Jhimruk river during the peak monsoon ranges from about 2000 to 6000 ppm with upper values ranging from about 20,000 to as high as 60,000 ppm, which indicated that the sediment transport in Jhimruk River during the monsoon was quite significant. The runners were significantly worn out after every monsoon. From the damages observed in the runners it was revealed that the runners in the power plant were exposed to too much higher sediment load than expected during the planning and design stage. The author developed a correlation between sediment load to which the turbine was exposed to and corresponding decrease in efficiency of the turbine over a time period and concluded that the efficiency loss was 4% at best efficiency point and 8% at 25% load. The results from the thermodynamic efficiency measurements obtained during his studies are shown in Fig. 6.

Thapa et al. [40] investigated the effect of suspended sediments in hydropower projects based on a case study of 60 MW Khimti hydropower plant. Due to the presence of high amounts of sediments, the hydropower plant was designed with settling basins to screen 85% of all particles with a fall diameter of 0.13 mm and 95% of all particles with a fall diameter of 0.20 mm. The plant was commissioned in July 2000 and the damage to the turbine components was investigated in July 2003. The investigators had observed that a significant amount of erosion had appeared in the turbine bucket and needles. Even though the settling basins were performing satisfactorily, particles smaller than the design size passed through the turbines and caused the damage. The bucket thickness was reduced by about 1 mm towards the root of the bucket, which is critical from the point of view of strength and hence the reliability of the component. Similarly, the splitter of the bucket was eroded to saw tooth form from the original straight edge. The sharp edge of the splitter

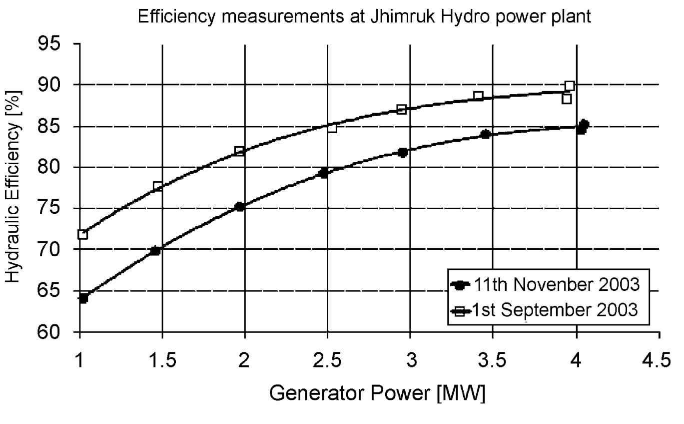

Fig. 6. Variation of thermodynamic efficiency [39].

had blunted and the width became approximately 4 mm due to which the efficiency of the turbine had decreased. To minimize the effect of erosion hard ceramic coatings were applied on the bucket and needle surface at the cost of around US$ 25,000 per runner, but performances were not promising.

Darling [41] studied the refurbishment of the Svartisen hydroelectric plant (Norway). The hydro turbine at this project experienced more erosion than other Francis units in Norway due to the unusually high levels of silt in the water. From the commissioning of the plant in 1993 until 2003, the efficiency of the turbine was dropped by 2–2.5%. Tungsten-carbide thermal spray coating, applied on site, was selected in an effort to increase the time between refurbishments, and to increase the lifetime of the turbine covers by as much as 16 years. Two years later, the performance of the turbine continued to meet their expectations.

5. Conclusions

Silt erosion in hydro turbines cannot be avoided completely, but can be reduced to an economically acceptable level. Many investigators have studied the process of erosion in hydro turbines through experimental and analytical studies. Few case studies are also reported in the literature. Some of the investigators have reported that in spite of design changes in the turbine components and providing different materials and coatings to the turbine blades, the improvement in most cases are not quite significant. Hence, further experimental and theoretical studies are required for studying the effect of hydro abrasive erosion in different flow conditions of turbines and parameters related to silt erosion in water.

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